Laser system

This invention relates to a laser system.

Laser diodes are well known as reasonably priced, small and robust sources of laser beams. Conventional laser diodes with small output power and good coherence properties have been available, and they are used in many applications such as CD players, bar-code readers etc.

More recently laser diodes with several Watts of output power have become available. These high-power laser diodes are potentially applicable in other areas such as the exposure of print plates in the graphical industry. However, these laser diodes have a large light-emitting area causing poor coherence properties of the output beams. The layout of the single emitters of such diodes has typical a width of some hundred μm, a height of 1-2μm and a cavity length of 0.5-2.5mm. In the direction of the width the light emitted by such diodes is multi-mode and has poor spatial coherence properties. In the direction of the height the emitted light is typically single-mode and has good coherence properties. The direction of high coherence is often referred to as the fast-axis (FA). The low-coherence direction is often referred to as the slow-axis (SA). The terms fast-axis and slow axis refer to the different degree of beam divergence in these two directions.

Hence, it is generally desirable to improve the coherence properties of the low coherences axis of high power multimode laser diodes. Such diodes can be either single-emitter diodes or diodes where several emitters are arranged in a configuration as a bar, a stack or an array. Furthermore, the diodes may be edge-emitting diodes, vertical cavity surface emitting lasers (VCSEL), Novalux Extended Cavity Surface Emitting Lasers (NECSEL), or the like. In the future, diodes with two low coherence axes will become available as well.

Due to the low coherence of the light emitted by high-power multimode laser diodes, the output beams from such laser diodes have a low beam quality

and a low brightness in the low coherence axis. This is inconvenient in applications where e.g. laser beams have to be focused into a small spot from a long distance.

Meanwhile these types of diode lasers are physically small and cheap compared to e.g. gas lasers. Therefore, high benefits can be obtained, if such laser diodes can be improved regarding the beam quality and the brightness.

The light emitted from high-power multimode laser diodes is known to comprise a plurality of modes among which the total amount of optical power is distributed. These modes radiate into different spatial angles, thereby causing a low brightness.

A measure of the quality of a laser beam is the beam quality factor M^2. A beam having an ideal Gaussian beam profile corresponds to a beam quality factor of $M^2=1$, while M^2 becomes larger for beams with a beam profile different from a standard Gaussian beam. The typical M^2 values of the low coherence axis of conventional high-power multimode laser diodes range from ten to several hundred, while the M^2 value of the high coherence axis typically is close to one.

The beam quality factor provides an indication of how well a laser beam can be focused and, thus, how small a focal point can be obtained. This property is very important in e.g. the graphical industry, where beams with e.g. a wavelength of 830nm and powers of 8W have to be focused into a 10μm spot over a distance of e.g. 300mm, in order to expose a printing plate. The size of the focal point is here a limiting factor for the resolution in the images that have to be transferred onto a printing plate by exposure in a computer-to-plate (CtP) process.

International patent application WO 02/21651 discloses a laser system comprising a laser diode and a reflector, where the laser diode and the

reflector define a cavity, and where the reflector reflects a selected part of the light beam emitted by the laser diode back into the diode as a feedback beam. The feedback light is further amplified in the laser medium and emitted as an output beam. According to the above prior art system, the reflector reflects a spatial mode having a mode number higher than a mode with maximum gain back into the laser diode.

Even though the above prior art system is known to work well on single emitter laser diodes with an emitter width of up to some hundred microns, it is a problem of the above prior art system that the output efficiency decreases with increasing emitter width, and the diode may be permanently damaged, if the output power is forced up by increasing the pump current.

The above and other problems are solved by a laser system comprising

- a laser diode member comprising a first surface for emitting a light beam with an intensity distribution around an optical axis, the light beam comprising a plurality of spatial modes each mode corresponding to a respective emission angle relative to the optical axis;
- first selection means for selecting a first part of the emitted light beam corresponding to a first one of said plurality of spatial modes emitted at a first emission angle on a first side of the optical axis;
- a first reflective member where the laser diode member and the first reflective member define a first cavity and where the first reflective member is adapted to reflect a first feedback fraction of the selected first part of the emitted light beam back into the laser diode member and to produce a first output beam corresponding to a first output fraction of the selected first part of the emitted light beam;
- second selection means for selecting a second part of the emitted light beam corresponding to a second one of said plurality of spatial modes emitted at a second emission angle on a second side of the optical axis opposite to the first side;
- a second reflective member where the laser diode member and the second reflective member define a second cavity and where the second

reflective member is adapted to reflect a second feedback fraction of the selected second part of the emitted light beam back into the laser diode member and to produce a second output beam corresponding to a second output fraction of the selected second part of the emitted light beam.

Consequently, a laser system with two cooperating cavities is provided, thereby providing a dual feedback that is at least partially symmetric with respect to the optical axis.

It has been realised according to the invention that by providing an at least partially symmetric dual feedback, the intensity distribution inside the laser diode becomes (partially) symmetric as well due to geometric properties of the gain. Therefore, the total power may be further increased compared to an asymmetric power distribution without causing local material destruction. This effect is even further pronounced for emitter stripes having a larger width. In one embodiment, the feedback from both reflective members is substantially symmetric and, in particular, of substantially equal strength.

It is a further advantage of the invention that the symmetric dual-cavity feedback introduces dynamical gratings in the amplifying medium of the diode laser, thereby providing efficient suppression of the spatial modes that are not fed back from the first and second reflective members in cooperation with the first and second selection means, respectively. Consequently, the emitted optical power is concentrated in substantially a single mode, thereby providing output beams with good coherence properties and a low M^2 value.

As the width of the diode is increased, the number of spatial modes is increased, thereby making an efficient mode-suppression even more advantageous. Hence, by increasing the feedback in the system according to the invention an improved mode selection is provided.

It is a further advantage of the invention that by adjusting the respective first and second feedback fractions, the symmetry of the feedback, i.e. the relative strength of the feedback fractions, may be adjusted. In a preferred embodiment of the invention, the first and second feedback fractions are substantially the same fraction, thereby providing a high degree of symmetry.

The intensity distribution of the emitted light around the optical axis defines a plane of low coherence and a plane of high coherence. The plane of low coherence is defined by the optical axis and the direction of low coherence, i.e. the slow axis, of the laser diode, and the plane of high coherence is defined by the optical axis and the direction of high coherence, i.e. the fast axis, of the laser diode. The spatial modes are emitted in corresponding directions within the plane of low coherence, i.e. at different emission angles relative to the optical axis and in the plane of low coherence. Hence, the filtering provided by the first and second selection means is provided along the direction of low coherence.

According to a preferred embodiment, the laser system further comprises third selection means for selecting a part of the emitted light beam in a direction across the plane of low coherence, i.e. a direction protruding from the plane of low coherence. Hence, a filtering of the emitted beam along the high coherence axis is provided, thereby preventing noise, e.g. caused by diffraction in lenses and scattering from surfaces, to be introduced in the feedback system and, thus, further improving the output power efficiency.

It is a further advantage of the invention that it provides a closed loop control of the feedback, thereby reducing the sensitivity to external disturbances and to variations of internal system parameters.

The laser diode member may comprise one or more emitters comprising a suitable amplifying medium. Examples of such laser diode members comprise broad-area laser diodes, preferably with large stripe width. Examples of semiconductor diode materials which may be used as

amplifying medium include but are not restricted to GaAs, InGaAlP, GaAlAs, InGaAs, and InGaAsP. According to yet another preferred embodiment, the laser system includes bars, stacks, arrays, or the like, thereby allowing to use emitters with a lower width while maintaining the total output power of the system. Hence, the number of modes is further reduced as well as some of the detrimental effects caused by wide diodes as described above and in the following.

The term selection means comprises any arrangement suitable for selectively allowing a part of the emitted light beam to reach at least one of the reflective members. Examples of such selection means comprise a spatial filter, such as a narrow slit or a filter having a differently shaped aperture, a grating, or the like. Furthermore, the selection means and the corresponding reflective member may be combined in a single element. For example, the reflective member may comprise a narrow stripe mirror where the edges of the mirror define a spatial filter, since only the part of the first light beam propagating in the direction of the mirror is reflected back into the laser diode.

It is further understood that one or more of the selection means may be combined in one device or arrangement, e.g. by providing a spatial filter with two slits and/or one or more rectangular apertures, or the like.

The reflective members may be partially transparent reflectors that reflect a certain fraction of the incident light and allow another fraction of the incident light to be transmitted through the reflector. Examples of such reflectors include mirrors, phase-conjugating mirrors, prisms, gratings, or the like.

In one embodiment, the first and second reflective members may be separate members, while, in another embodiment, they may be combined in a single reflective member.

It is preferred that each of the plurality of spatial modes is associated with a corresponding mode number; and that the first and second selection means

are adapted to select corresponding first and second spatial modes associated with corresponding first and second mode numbers where the first mode number is equal to the second mode number. Consequently, the two selection means are adjusted to select the corresponding lobes of a twin-lobe distribution corresponding to substantially a single mode, i.e. if the first selection means selects the N-th mode in a first half-plane with respect to the optical axis an in the direction of the slow axis, the second selection means selects the N-th mode in the corresponding other half-plane with respect to the optical axis. Consequently, by selecting two mirrored lobes, the system is stabilised, since any mode-competition is suppressed.

It is understood though, that in an alternative embodiment an oscillating system may be obtained by selecting lobes corresponding to different modes in the respective half-planes. In this case, a mode competition between the selected modes may change the energy distribution between the two modes over time. This situation may be utilised to cause the total energy alternatingly to be concentrated in the two modes, thereby providing an oscillating system.

Inside the laser diode all the modes that overcome the lasing condition exist as small individual laser beams that radiate into different spatial angles. These angles of propagation are related to the wavelength of the individual mode. The different modes cannot be distinguished easily from each other because they here are mixed up in space; the regime of Fresnel diffraction is said to exist here. In a distance from the diode much larger than the confocal parameter, Fraunhofer diffraction is said to exist. The properties of these two regimes are often referred to as the near-field and the far-field, respectively. For the purpose of the current description, a difference between these two types of diffraction is the fact that the modes are spatially separated from each other in the regime of Fraunhofer diffraction, and not in the regime of Fresnel diffraction. Consequently, a spatial filter can perform individual mode-selection in the regime of Fraunhofer diffraction only.

However, the far-field may be generated as a Fourier-transform of the near-field and vice versa. Consequently, a mode-selective system with a length much smaller than the distance to the far-field can be obtained by the use of optical components that act as a Fourier-lens.

Hence, in another preferred embodiment, the system further comprises at least one optical element for producing an optical Fourier transformation of the emitted light beam in a diffraction plane of said at least one optical element and that at least one of the first and second selection means is placed substantially in the diffraction plane of the at least one optical element.

For the purpose of this description, the diffraction plane is also referred to as the Fourier-plane, because it is the plane in which a Fourier lens returns the result of the corresponding Fourier-transformation. In the diffraction planes or in the far-field, the individual modes included in the optical output from the laser diode are separated in space due to the differences in their angles of propagation. When placed in the diffraction plane or in the far-field, the spatial filters provide a mode-filtering which can perform an individual mode selection.

In many commercially available laser diodes, the light emitting facet and the back facet opposite to the light emitting facet are coated in order to provide an efficient laser cavity and an efficient output coupling of the laser beam. Normally the back-facet is high-reflectivity (HR) coated providing a reflectivity larger than 90%, thereby defining one end of the laser cavity opposite the end defined by the first and second reflective members, respectively. Alternatively, instead of providing a laser diode with a reflective back facet, other forms of reflective members may be used, e.g. a grating, en external mirror or grating, or the like.

The front-facet of a commercially available laser diode is normally coated with an antireflective (AR) coating with a reflectivity around 8 to 10%. This is

a preferred choice when running the diodes without external cavities. However, when the diode is operated according to the invention, the reflectivity of the AR-coating on the front facet may be utilised to control the influence of the feedback. On the one hand, it is desirable to reduce the reflection coefficient of the AR-coating on the front facet, because it causes a higher in-coupling and it results in lower amplification of the modes not selected in the feedback system. This is due to the fact that a lower reflection causes the threshold value of the diode to increase, thereby increasing the effect of the mode suppression of non-selected modes. On the other hand, the reflection coefficient should not become so low as to prevent the lasing process to be initiated.

Hence, in a preferred embodiment, the laser system further comprises an antireflective coating on the first side, i.e. the front facet, of the laser diode member, the antireflective coating providing a reflectivity between 0.05% and 20%, preferably between 0.1% and 2%.

In yet another preferred embodiment, the first and second selection means comprise respective first and second gratings embedded in the laser diode member, the first and second gratings defining an angle between them corresponding to the emission angle of the selected spatial mode.

Consequently, by integrating the selection means into the laser diode, a particularly compact laser system is provided.

According to a further preferred embodiment, the first surface of the laser diode member comprises a first and a second area defining an angle between them corresponding to the emission angle of the selected spatial mode, and that the first and second reflective members comprise corresponding reflective coatings on the corresponding first and second area. Hence, by further integrating the reflective members into the laser diode, an even more compact laser system is provided.

It is a further advantage of an integration of the selection means and reflective members that the laser system becomes more robust against disturbances such as vibrations, temperature fluctuations, etc.

It is a further advantage of an integration of the selection means and reflective members that no alignment of these components is required.

In another preferred embodiment, the system further comprises a modulator element for modulating at least one of the first and second output beams. Consequently a laser system is provided that may provide a modulation of the laser beam, e.g. in order to provide an alternating sequence of on and off periods. For example, the modulator element may comprise an acousto-optic modulator, an electro-optic modulator, a spatial light modulator such as a Grating Light Valve (GLV) spatial light modulator, a MEMS spatial light modulator, a conformal grating electromechanical system (GEMS), a liquid-crystal spatial light modulator, or any other suitable modulator device. In one embodiment the modulator element comprises the laser diode in combination with a modulated pump current.

The present invention can be implemented in different ways including the system described above and in the following, a method of aligning such a system, applications of such a system in the graphical industry, and further product means, each yielding one or more of the benefits and advantages described in connection with the first-mentioned system, and each having one or more preferred embodiments corresponding to the preferred embodiments described in connection with the first-mentioned system and disclosed in the dependant claims.

According to another aspect of the invention, the beam quality of the above prior art system may be improved by a laser system comprising

- a laser diode member comprising a first surface for emitting a light beam with an intensity distribution around an optical axis, the light beam

comprising a plurality of spatial modes each mode corresponding to a respective emission angle relative to the optical axis;

- at least one optical element for producing an optical Fourier transformation of the emitted light beam in a diffraction plane of said at least one optical element;
- first selection means for selecting a first part of the emitted light beam corresponding to a first one of said plurality of spatial modes emitted at a first emission angle on a first side of the optical axis;
- a reflective member where the laser diode member and the reflective member define a cavity and where the reflective member is adapted to reflect a feedback fraction of the selected first part of the emitted light beam back into the laser diode member;
- second selection means for selecting a second part of the emitted light beam corresponding to a second one of said plurality of spatial modes emitted at a second emission angle on a second side of the optical axis opposite to the first side, and that the second selection means is placed substantially in the diffraction plane of the at least one optical element.

Hence, by positioning a second selection means substantially in the diffraction plane, mode-selective filtering of the output beam is provided, thereby improving the M^2 and the output power of the laser system. This improvement is due to the fact that the additional spatial filter actually performs, when placed substantially in the diffraction plane, a mode-selection rather than a simple beam cutting.

According to a preferred embodiment, each of the plurality of spatial modes is associated with a corresponding mode number; and that the first and second selection means are adapted to select corresponding first and second spatial modes associated with corresponding first and second mode numbers where the first mode number is equal to the second mode number. Hence, the mode for which feedback is provided in the first cavity is selected by the second selection means.

According to yet another aspect of the invention, the beam quality of the above prior art system may be improved by a laser system comprising

- a laser diode member comprising a first surface for emitting a light beam with an intensity distribution around an optical axis defining a plane of low coherence and a plane of high coherence, the light beam comprising a plurality of spatial modes each mode corresponding to a respective emission angle relative to the optical axis and in the plane of low coherence;
- first selection means for selecting a first part of the emitted light beam corresponding to a first one of said plurality of spatial modes emitted at a first emission angle on a first side of the optical axis in the plane of low coherence;
- second selection means for selecting, in a direction across the plane of low coherence, a second part of selected first part of the emitted light beam;
- a reflective member where the laser diode member and the reflective member define a cavity and where the reflective member is adapted to reflect a feedback fraction of the selected second part of the emitted light beam back into the laser diode member.

Hence, a filtering of the emitted beam along the high coherence axis is provided, i.e. a direction protruding from the plane of low coherence, thereby preventing noise, e.g. caused by diffraction in lenses and scattering from surfaces, in the feedback system and, thus, further improving the output power efficiency.

The invention further relates to a method of aligning a laser system as described above and in the following, the method comprising

- measuring a predetermined property of the emitted light beam while the second selection means and the second reflective member are deactivated;
- adjusting at least one of the position and the orientation of at least one of the first reflective member and the first selection means to obtain an

emitted light beam having a predetermined value of the measured predetermined property;

- activating the second selection means and the second reflective member to cause the laser system to produce a first and a second output beam;
- measuring a predetermined measure of quality of the first and second output beams;
- adjusting at least one of the position and the orientation of at least one of the second reflective member and the second selection means to improve the measured predetermined measure of quality of the first and second output beams.

Consequently, an efficient method of aligning a laser system according to the invention is provided. It is an advantage that an efficient mode selection is provided, and a high output efficiency is achieved. It is a further advantage that a high beam quality is achieved.

By first aligning the first selection means and the first reflective member with the second selection means and the second reflective member being deactivated, a mode is selected by the first feedback cavity. In the subsequent step of aligning the components of the first and the second cavity, it is ensured that the same mode is selected in both cavities, thereby avoiding mode competition.

Here the term deactivating the selection means comprises causing the selection means to substantially select all modes in the emitted light beam on the corresponding side of the optical axis. For example, this may be achieved by substantially completely opening an aperture of a spatial filter, by removing the spatial filter from the light path, etc. Correspondingly, deactivating the reflective member comprises causing the reflective member not to reflect any part of the emitted light beam back into the diode laser, e.g. by removing or blinding off of the reflective member. Accordingly, activating a selection means and/or a reflective member comprises causing them to

select the desired part of the emitted light beam and to reflect the desired part of the emitted light beam back into the laser diode, respectively.

The predetermined property used for determining an alignment of the first selection means and the first reflective member may be any suitable property for determining a desired mode selection. In a preferred embodiment the predetermined property is the shape of the intensity distribution of the first light beam. In a further preferred embodiment the predetermined shape is characterised by a comprising a narrow peak in the far-field of the emitted light beam that comprises most of the emitted optical power.

According to another preferred embodiment of the invention, the predetermined property is a measure of the ability of the emitted light beam to be focused, preferably the M^2 value of the output beam.

Similarly, the measure of quality used for aligning the first and second selection means and the first and second reflective members may comprise any of the above properties. For example, the measure of quality may comprise the total output power of the first and second output beams, the M^2 values of the first and second output beams, or the like.

The invention further relates to the use of the laser system described above and in the following in the graphical industry, e.g. in an image setting machine.

In particular, the laser system may advantageously be used in connection with an internal drum image setting system.

Hence, the invention further relates to an internal drum image setting system comprising

- a drum member having an inner surface for receiving light sensitive material
- a support member mounted movably relative to said drum member, preferably inside the drum member;

- a laser system as described above and in the following for producing at least two output beams where the laser system is mounted on said support member;
- at least one optical element for defining respective beam paths for the at least two output beams and for focussing the at least two output beams on the light sensitive material; and
- means for directing the at least one output beam towards predetermined positions on the inner surface of the drum member.

In a particularly compact embodiment, the means for directing the at least one output beam towards predetermined positions on the inner surface of the drum member comprises a pivotally mounted mirror in the beam path of at least one of the output beams, where the pivotally mounted mirror is controlled, cooperatively with the movably mounted support member, to direct the at least one output beam towards predetermined positions on the inner surface of the drum member. Alternatively, other arrangements for directing the focus point of the output beam(s) to different positions on the inner surface of the drum member may be provided, e.g. by providing a rotating drum and/or a drum which may be moved along its longitudinal axis.

In an internal drum image setting system, the focus point on the drum should be a circular or a square with a Gaussian intensity distribution. However, due to the coherence properties of the two beams produced by the laser system according to the invention, if the two beams are focussed onto the same area, interference stripes may be formed across the focus spot, which create a non-uniform intensity distribution.

According to a preferred embodiment, the at least one optical element further comprises a quaterwave plate inserted in the beam path of one of the output beams.

By inserting a quarterwave plate in one of the beams, one beam will be linear polarized and the other will be circular polarized and, therefore, interference

stripes at the focus point will be inhibited. The same method may be extended to a larger number of beams than two beams. In an alternative embodiment, an halfwave plate may is used.

The invention will be explained more fully below in connection with a preferred embodiment and with reference to the drawing, in which:

figs. 1a-b show a schematic view of a laser system according to an embodiment of the invention;

fig. 2 shows a schematic perspective view of a laser diode for use in a laser system according to an embodiment of the invention;

figs. 3a-c show scans along the slow and fast axis of the far-field of laser diodes for use in a laser system according to the invention;

figs. 4a-e show schematic views of examples of optical arrangements including Fourier lenses;

figs. 5a-c show schematic views of examples of a laser system without Fourier lenses;

figs. 6a-c illustrate examples of spatial filters for selecting spatial modes according to an embodiment of the invention;

fig. 7 illustrates the generation of dynamic gratings in the amplifying medium in a laser system according to an embodiment of the invention;

fig. 8 illustrates a calculated far-field interference pattern of a laser diode.

fig. 9 shows a block diagram of a closed loop control system corresponding to an embodiment of the invention;

figs. 10a-d show schematic views of examples of reflective members for use in an embodiment of the invention;

fig. 11 shows a schematic view of a laser system producing four output beams according to an embodiment of the invention;

figs. 12a-b show a schematic view of a laser diode with an integrated feedback system according to an embodiment of the invention;

figs. 13a-b show a schematic view of a laser diode with an integrated feedback system according to another embodiment of the invention;

fig. 14 shows a schematic perspective view of a laser system including a stack of single-emitter diodes according to an embodiment of the invention;

fig. 15 shows a schematic view of a laser system including an bar of single-emitter diodes according to an embodiment of the invention;

fig. 16 shows a flow diagram of a method of aligning a laser system according to an embodiment of the invention;

fig. 17 shows a schematic view of a configuration of a laser system during alignment according to an embodiment of the invention;

fig. 18 shows a far-field profile obtained during alignment of a laser system according to an embodiment of the invention;

fig. 19 shows examples of far-field profiles of a laser system according to an embodiment of the invention;

fig. 20 shows a schematic view of a laser system according to an embodiment of the invention including a modulation prior to a polarization coupling;

fig. 21 shows a schematic view of a laser system according to an embodiment of the invention including a modulation after a polarization coupling;

fig. 22 shows a schematic view of a laser system according to an embodiment of the invention including a modulation in combination with beam focussing;

figs. 23a-b illustrate the use of a laser system according to an embodiment of the invention in an internal drum image setter;

fig. 24 shows a schematic view of an internal drum image setter including a laser system according to an embodiment of the invention;

fig. 25 shows a schematic view of an internal drum image setter including a laser system according to another embodiment of the invention;

figs. 26a-b show a schematic view of a laser system according to an embodiment of the invention.

Figs. 1a-b show a schematic view of a laser system according to an embodiment of the invention. A laser system according to the invention generates mode-selective optical feedback from an external cavity of one or more multimode laser diode(s) 101. Spatial filters 109 placed in a diffraction-plane 103 of an optical component 108, e.g. a Fourier-lens, or in the far-field of the optical output of the laser diode 101, together with two external reflective elements 106 and 112, e.g. dielectric mirrors, generate a mode-selective optical feedback into the laser diode 101. This causes the output beam properties to change, and output beams 113 and 114 with an M^2 value less than two and with an improved brightness are achieved.

The multiple feedback into the diode generates a dynamical grating inside the active region of the laser diode(s). This grating is generated due to interference between the selected single-mode feedback beams causing electron diffusion in the active region. A grating with the same layout as the interference pattern is thereby obtained. The modes that are used for multiple feedback are, due to the cavity construction, coupled to each other and, therefore, they are actually the same mode. This provides good conditions for the interference grating.

The gain properties of individual modes inside the diode are controllable because non-selected modes experience less gain, while selected modes experience extra gain due to the feedback. Furthermore, the non-selected modes are suppressed by the introduced dynamical grating inside the diode(s), since the grating is optimised to only diffract the mode that created it. The introduced dynamical grating together with the spatial filters strongly improves the gain conditions for a single mode and suppresses the remaining modes. This allows substantially a single mode to exist, only.

In order to generate an efficient dynamical grating inside the active region of the diode it is advantageous that only two beams originating from a single mode (e.g. mode N) interact to form the dynamical gratings. If beams originating from other modes, for instance neighbour modes (e.g. modes N-1 and N+1), interfere with the previously mentioned mode N, a dynamical grating is created which is not optimised with respect to mode suppression of unwanted modes. Due to interference of neighbour modes, the ideal gratings that would have been formed by the feedback of a single mode are washed out, thereby preventing an efficient suppression of neighbour modes. Furthermore, it is advantageous to have only two beams originating from a single mode in the in beginning of the process of the formation of dynamical gratings in order to avoid mode competition or coupling between neighbour modes. This is achieved by the use of spatial filters in combination with feedback mirrors.

The overall power of the multimode low coherence axis is concentrated into a single-mode with a good beam quality corresponding to the single-mode of the high coherence axis.

Fig. 1a shows a planar view of the laser system in a plane of low coherence including the low coherence axis (SA), while fig. 1b shows a planar view of the laser system in a plane of high coherence including the high coherence axis (FA).

Referring to fig. 1a, the laser system comprises a multimode diode laser 101 having a light-emitting active area on a front facet 116. In the direction of the low coherence axis (SA), the emitted light corresponds to a plurality of spatial modes, each corresponding to a twin-lobe profile around the optical axis 107 generally designated as z-axis. The laser system further comprises an optical component 108, e.g. a Fourier lens, having a corresponding diffraction plane 103. A spatial filter 109 is placed in the diffraction plane 103. The spatial filter provides two apertures 110 and 111, each selecting a part of the emitted light beam corresponding to the lobes of a selected spatial mode. For example, the spatial filters may provide two slits 110 and 111. The laser system further comprises partly transparent reflective elements 106 and 112, e.g. dielectric mirrors having a reflective index less than 100, e.g. 50%, each reflecting the modes selected by the apertures 110 and 111, respectively, back into the laser diode 101. The partly transparent reflective elements 106 and 112 allow a fraction of the emitted light beam to be transmitted, thereby generating two output beams 113 and 114.

The partly transparent reflective elements may comprise one or more dielectric mirrors. A dielectric mirror has the advantage that it reduces disturbances of the output beams due to scattered light. Alternatively other types of mirrors may be used, e.g. metal mirrors, phase-conjugating mirrors, gratings, etc. The mirrors may be planar, spherical, etc.

It is further noted that, alternatively to a partly transparent mirror, a partially transparent reflective element may comprise a non-transparent reflector combined with other means of output-coupling a fraction of the intensity from the dual cavity, e.g. a beam splitter.

It is understood that the two reflecting elements 106 and 112 may be provided as sections of a common reflector. For example, if a collimated beam is used, the reflector may be a flat mirror, where different sections of the mirror function as two reflective elements. In the case where a non-collimated beam is used, a single spherical mirror can be used. The angle between the respective reflecting surfaces of the reflecting elements and the z-axis 107 may be 90° or different from 90° in order to optimise the optical feedback.

Hence, the laser system generates two coupled output beams 113 and 114. These two beams are coupled to each other through an optical closed loop made up by the diffraction in the dynamic gratings inside the diode and by three mirrors: The diode 101 and the two partially transparent reflective elements 106 and 112. Hence, the laser system generates a dual external feedback. The reflection coefficients of the two partially transparent reflective elements 106 and 112 control the ratio between the amounts of power used for the feedback vs. output. Furthermore, if the two partially transparent reflective elements do not have the same reflection coefficient, they introduce asymmetric feedback into the diode, thereby allowing controlling the properties of the dynamical grating introduced in the active region. Hence, the ratio between the powers in the two output beams can be controlled.

According to the invention, the two filter apertures 110 and 111 in the SA Fourier-plane are adjusted to each select a mode that can be mirrored in the z-axis 107, i.e. at angles θ and $-\theta$, respectively. That is, one filter selects the N-th mode in one half-plane and the other filter selects the N-th mode in the corresponding other half-plane with respect to the z-axis in fig. 1a. Hence, on

both sides modes with the same mode number N are selected, thereby avoiding mode competition, and providing a stable laser output.

It will be appreciated that, in practice, the lobes of the mode N may be emitted into angles $\theta+\delta$ and $-\theta$ where δ is a small deviation of the ideal situation where the lobes are emitted into angles θ and $-\theta$. In order to compensate for non-ideal diodes where the lobes of a mode are emitted into angles $\theta+\delta$ and $-\theta$ the position of the two filter apertures 110 and 111 can be adjusted independently of each other.

It has been realised in experiments that, in the Fourier plane, the modes do not necessarily exist as a perfect discrete distribution in space. Instead, the modes may overlap and there may be noise due to diffraction, aberrations, etc. Consequently, the widths of the apertures 110 and 111 may be adjusted to select the contribution of the desired mode and its nearest neighbours to be included in the feedback. In this way it is possible to minimise or even remove the destructive effect from neighbour modes on the formation of dynamical gratings. Therefore, the possibility of adjusting the widths of the apertures 110 and 111 is advantageous in order to obtain high efficiency and high beam quality of the laser system.

It is noted that the diode may be regarded as a mirror in more that one way. As will be described in more detail below, the diode comprises a front facet which is AR-coated providing a small reflectivity. Hence, the front facet reflects a part of the feedback beams. This part of the beam will not get extra gain, because it never enters the active region of the diode. The back facet of the diode is HR-coated (normally around 90% reflection or more), thereby acting as a mirror. The dynamical grating inside the diode 101 allows diffraction of the mode that created it.

Now referring to fig. 1b, in the high coherence axis (FA), a filtering is performed in the high coherence axis, thereby improving the beam quality along this axis, as well. The reason for this is that imperfections in e.g. the

optical components lower the beam quality of this axis and reduce the beam quality of the feedback beams, thereby reducing the beam quality of the output, too. The filtering may be regarded as a frequency filtering, since it is performed as a spatial filtering in the Fourier plane of an optical component. Hence, the laser system comprises an optical component 104, e.g. a Fourier lens, having a diffraction plane 102. A spatial filter 105 for selecting a part of the emitted beam in the direction of the high coherence axis (FA) is placed in the diffraction plane 102. Furthermore, in fig. 1b, one of the feedback mirrors, designated by reference numeral 106, is shown as well. The second feedback mirror (112) and lens 108 are not shown in this view.

In the high coherence axis of multimode diodes usually only one mode is present. Hence, a mode-selective filter is not necessary in this direction. However, filtering of the beam in the FA-direction by the filter 105 increases the beam quality, as it removes noise e.g. due to diffraction, aberrations etc., due to optical elements, or the like. Hence, filtering of the beam in the FA-direction by the filter 105 also prevents destructive interference inside the diode of light from the selected mode with unwanted light from diffraction, aberrations etc. Consequently, a reduction in the efficiency of the dynamical gratings inside the laser diode is avoided by using a filter in the FA-direction.

In one embodiment, lenses 108 and 104 are cylindrical lenses placed in different planes.

In the following, the individual components of the above laser system are described in more detail.

Fig. 2 shows a schematic perspective view of a laser diode for use in a laser system according to an embodiment of the invention. The laser diode 101 is a multimode diode laser, e.g. a multimode Ga(Al)As laser diode with an emitter 204 having a width 206 between 100 to 1000μm and a height 205 of 1-2μm. The length 207 of the internal cavity is typically between 0.5 and 2.5 mm. For example, these types of diodes are available for wavelengths

between 780 to 850nm providing an optical output power that may vary from below 2W up to 10W or more.

The diode 101 provides an amplifying medium when a pump current is applied to it via electrodes 201. In a conventional laser diode, two opposing end facets are coated with a reflective coating, thereby generating a laser cavity between them. If one of the end facets – the so-called back facet – is coated with a high-reflectivity (HR) coating 202 and the opposite end facet – the so-called front facet 116 – is coated with an anti-reflective (AR) coating 203, a laser beam is emitted from an active region 204 of the front facet along the optical axis 107. For example, the HR coating may provide a reflectivity of 90% or higher, while the AR coating in conventional diodes provide a reflectivity between typically 8% and 10%. These coatings determine the properties of the cavity mirrors of the diode and, thus, the amplification ratio vs. the optical output ratio.

According to the invention, a high degree of in-coupling from the feedback beam is desired. A suitable choice of the reflectivity of the AR-coating on the front facet may control the relative influence of the contributions from the internal and the external cavities, respectively. On one hand, it is advantageous to minimize the reflection coefficient of the AR-coating on the front facet, thereby providing a higher in-coupling of the feedback, resulting in relatively lower amplification of the modes that are not selected in the feedback system. This is due to the fact that a lower reflection causes the threshold value of the diode to increase, thereby increasing the effect of mode suppression. Thus, the non-selected modes are further suppressed, and preferably they cannot overcome the lasing condition and vanish. On the other hand, the reflection coefficient should not be chosen too low, since in that case the lasing process will never start. Hence, according to the invention, values of 0.05% to 20% reflectivity are preferred. In the case of completely symmetric feedback reflection coefficients between 0.05% and 1%, more preferably between 0.05% and 0.5% are preferred, while larger reflection coefficients are preferred in the case of asymmetric feedback.

The emitted laser beam has a low coherence axis in the direction (SA) of the width 206 of the emitter stripe 204 and a high coherence axis along the direction (FA) of the height 205 of the emitter stripe 204. The polarization of a single emitter diode is linear, e.g. perpendicular or parallel to the low coherence axis.

In some diodes, the emitter stripe 204 is segmented into a number of segments. This is similar to a so-called diode bar where several emitters are placed next to each other. However, in the segmented diode these emitters originate from the same emitter. The emitter is divided into several subsections, e.g. by the introduction of damages having a width of a few microns into the lasing material, or by introducing such periods into the electrodes 201.

Figs. 3a-c show scans along the slow and fast axes of the far-field of a laser diode as shown in Fig. 2. The shapes of the curves in figs. 3a and 3b are referred to as the far-field profile for the low (SA) and high (FA) coherence axes, respectively. The examples of figs. 3a-b are obtained for a 3W diode having a wavelength of 808nm and an emitter stripe of 200μm x 1μm by Coherent Inc, while fig. 3c shows a far-field profile of a different diode.

Fig. 3a shows a scan of a beam profile along the low coherence axis of a laser diode as described in connection with fig. 2. Each curve shows a cross scan along the low coherence axis and through the centre of the profile in the high coherence axis (as shown in fig. 3b). The scans are obtained by a high resolution scanning technique. The different curves correspond to different levels of drive current to the diode, and thereby different output powers: Curve 301 corresponds to 3000mA, curve 302 corresponds to 2500mA, curve 303 corresponds to 2000mA, curve 304 corresponds to 1500mA, curve 305 corresponds to 1000mA, and curve 306 corresponds to 500mA. The individual modes can be seen as small spikes on the curves.

In general, for drive currents above the threshold current, the far field profiles along the low coherence axis have an M-shape. However, the detailed shape may be different from diode type to diode type – and even from diode to diode of the same type. Among other things, the shape is dependent on the geometry of the diode (the width and the length of the cavity). Furthermore, the drive current has a strong influence as seen in fig. 3a.

It can further be seen from fig. 3a, that the SA far-field profiles have a certain degree of symmetry around the centre, i.e. around the optical axis. However, the degree of symmetry depends on the individual diode. Normally, high-quality diodes of the same type are almost similar in their far-field profile and they have a substantially symmetric far-field profile.

The far-field profile may be changed by applying optical feedback into the diode. The change in the far-field profile corresponds to a change in the distribution of the total output power between the individual modes in the output beam. It is desirable to concentrate as much of the output power as possible into a single one of the modes without causing damages to the diode material.

A single mode with a mode number higher than the lowest-order mode shows two peaks in the far-field located at angles θ and $-\theta$. A lowest order mode corresponds to an angle $\theta=0$, i.e. an emission along the optical axis, while higher order modes correspond to larger emission angles. For each higher order mode with a peak at angle θ, there is a symmetric peak with the same properties on the other side of the optical axis. Hence, one peak is radiating with an angle θ, and the other one with angle $-\theta$. These two peaks are in principle independent of each other. However, via the feedback introduced by the laser system according to the invention, they become highly dependent on each other through closed loop optical feedback, and they may be regarded as a single mode with a twin-lobe profile, i.e. with lobes at emission angles θ and $-\theta$. This gives rise to the special coupled two-beam output of this laser system.

It should be noticed that more and more modes can overcome the lasing condition as the drive current is turned up, and therefore more and more modes will exist in the output beam. Consequently, the divergence of the output beam changes in the SA-direction as a function of the drive current, as can be seen from fig. 3a. Hence, the optimal mode-selection for feedback depends on the drive current. Furthermore, one can provoke a normally none existing mode at a given drive current to exist by changing the properties of the gain for the individual modes. As will be described below, the above properties are taken into account in a mode-selection procedure according to the invention.

Fig. 3b shows a scan of a beam profile along the high coherence axis of a laser diode as described in connection with fig. 2. Each curve shows a cross scan along the high coherence axis and through the centre of the profile along the low coherence axis. The scans are obtained by a high resolution scanning technique. The different curves correspond to different levels of drive current to the diode, and thereby different output powers: Curve 312 corresponds to 2500mA, curve 313 corresponds to 2000mA, curve 314 corresponds to 1500mA, curve 315 corresponds to 1000mA, and curve 316 corresponds to 500mA. In this direction it can be seen that only one mode exists. Furthermore, figs. 3a-b illustrate that the width of the profile is larger along the high coherence axis, i.e. the beam diverges faster along this axis. In the example of figs. 3a-b, the angle of divergence is over 40° in the high coherence axis, whereas the angle of divergence in the slow-axis on is only 12°.

Fig. 3c shows a far-field profile along the low coherence axis of a laser diode for use in a preferred embodiment of the invention. The diode is a single stripe diode with an emitter width of 1000µm providing an output power of 10W at 830nm.

Figs. 4a-e show schematic views of examples of optical arrangements including Fourier lenses.

Fig. 4a illustrates the generation of a Fourier transformation by the optical component 108 in the low coherence direction (SA) of a laser system as shown in figs. 1a-b. As described above, the laser diode 101 emits light corresponding to different modes at different angles θ from front facet. In fig. 4a, light beams 400 corresponding to a single mode are illustrated. This mode is emitted from the whole surface of the laser. The rays of this mode propagate parallel to each other at an emission angle θ, until an interaction with the lens 108 takes place in the distance of s_1 from the centre 401 of the laser diode.

An advantageous property of the Fourier transformation in the low coherence axis is that the beams corresponding to one mode end up in the same point in the Fourier plane irrespective of the width of the laser diode. This has the advantage that the effect of the mode selection technique described here is independent of the width of the diode. A further advantage is that this technique for mode selection is ideal for other types of laser diodes such as laser arrays or laser bars, because the Fourier transformation is independent of the width of the light emitting device.

It is noted that, due to the astigmatic behaviour of a laser diode, the beam in the SA is seen to originate from the centre of the diode, whereas the beam in the FA is seen to originate from the surface of the diode.

There is a beam waist in the centre of the diode 101 that corresponds to the object in this setup. Hence, the plane 401 may be regarded as the object plane. The lens 108 produces an image of the near-field in an image plane 403 at a distance s_2 from the lens 108. In a distance from the lens 108 corresponding to the focal length f of the lens 108, the rays of the mode radiating at angle θ meet in space at the point P in the diffraction plane 402. The position of the point P within the plane 402 is a function of the angle θ,

the distance s_1, and of the focal length f. Hence, the lens 108 transforms an angle of incidence θ onto the lens into a position P in the diffraction plane 402. The modes that propagate at different angles are mapped to different positions in the diffraction plane.

Thus, the modes are separated into space. Since a number of modes with a discrete distribution in their propagation angles exist in the light beam emitted from a multimode laser diode, these modes are discretely distributed in the diffraction plane. If a screen is placed in the diffraction plane, a pattern of linear fringes are seen where each fringe correspond to one mode. It is understood that the pattern is two-dimensional where one axis corresponds to the FA corresponding to a single mode and the other one to the SA corresponding to several modes. Therefore, the pattern is made up of lines. If the diode had two low coherence axes, a pattern of dots would be obtained.

Hence, in the diffraction plane 402, the modes may be separated in space. Correspondingly, when placed in the diffraction plane 402, the spatial filter 109 of fig. 1a functions as a mode filter in correspondence with the invention. It is understood that small displacements, e.g. smaller than 10%, preferably smaller than 5%, of the focal length of the Fourier lens, from the diffraction planes still allow a distinction of different modes in space. However, the further away from the diffraction plane, the spatial filtering is performed, the less mode-selective the spatial filter is. Far away, i.e. further than the confocal length, from the diffraction plane, the spatial filter would merely act as a beam cutter.

It should be noted that, in the above discussion, nothing requires the rays 400 to originate from a single diode. For example, alternatively the three rays could originate from three diodes arranged as a bar. It is the angle of propagation that is important. Hence, according to one embodiment of the invention bars, arrays, etc., may be used instead of just single emitter diodes, thereby further increasing the output power.

It is preferred that all optical elements used for making such a Fourier-transformation are aberration free (diffraction limited) and well aligned, thereby providing a high-quality optical Fourier-transform that resembles the real far-field as closely as possible. If the lens e.g. introduces aberrations or if it is misaligned, the pattern in the diffraction plane does not equal the pattern in the far-field.

Furthermore, it is preferred that the distance between the spatial filter 103 and the mirrors 106,112 in figure 1a is as small as possible, in ideal the distance should be zero. In order to obtain the optimum feedback reflection from the feedback mirror the surface of the mirror should be placed in the Fourier plane. In order to obtain this it is possible to displace the filter a small distance in front of the Fourier plane (e.g. 50 μm) with no appreciable difference in the efficiency of the mode selection.

When constructing an optical system for use in a laser system according to the invention, the following aspects should be considered: Firstly, the emitter of the laser diode 101 is much wider than it is high. Secondly, a laser diode has astigmatism. The object point of the FA and the SA is not located in the same plane along the z-axis. The object point is the beam waist of the respective FA and SA part of the beam in the diode region. The object point of the SA is located at the centre of the cavity, as illustrated by reference numeral 401 in fig. 4a, whereas the object point of the FA is located at the front facet 116.

Figs. 4b-c illustrate an embodiment of the optical system for making a Fourier-transformation that is constructed from one-axis optics e.g. aspherical cylindrical lenses that work on one axis at a time. According to this embodiment, at least two lenses 104 and 108, one for the FA- and one for the SA-direction, are used. This results in the case where the Fourier-planes 404 and 405 of the FA and the SA, respectively, may be located in two different z-planes, i.e. they do not necessarily coincide. In the embodiment of figs. 4b-c, the lenses 104 and 108 produce a collimated beam.

The use of separate lenses for the FA and SA, respectively provides the opportunity to separate the FA- and SA-filtering into two different locations, which is less mechanical demanding. The use of separate lenses with different focal lengths further has the advantage that the lenses provide magnification in the two directions, thereby improving the imaging of the wide and narrow stripe and, secondly, allowing the output beams to be made circular (or squared) rather than elliptic (or rectangular). This removes the need of such compensations after the external cavity.

In an alternative embodiment, a common optical component acting in both the slow and the fast axis may be used. Such a combined lens has the advantage that it only requires the alignment of one collimation.

The system of figs. 4b-c provides a Fourier-transformation in a collimated beam, thereby producing a collimated output beam after the external cavity, and the requirements on the tolerances of the filter system are low due to high magnification in the diffraction-plane.

In this configuration, the partially transparent reflective elements (not shown in figs. 4c-d) may be plane mirrors, phase conjugating mirrors, or the like.

It is noted that in the above configurations, the lens 108 is not shown in fig. 4b and lens 104 is not shown in fig. 4c.

Figs. 4d-e illustrate an embodiment of the optical system for making a Fourier-transformation that is constructed from one-axis optics and provides a focussed beam. In some situations it may be easier to avoid astigmatism by focusing the SA- and the FA-axis independently into the same z-plane rather than collimating the two parts of the beam equally by two lenses. An embodiment of a focussing Fourier system is shown in figs. 4d-e. In figs 4d-e reference numerals 406 and 408 refer to the Fourier planes of the FA and the SA, respectively, while reference numerals 407 and 409 refer to the image

planes in the FA and the SA, respectively. In one embodiment the lenses 104 and 108 are aspherical cylinder lenses that produce a focused beam in the FA and the SA, respectively.

It is an advantage of this embodiment that the astigmatism is removed.

It is noted that in the above configurations, the lens 108 is not shown in fig. 4d and lens 104 is not shown in fig. 4e.

In one embodiment, the partially transparent reflective elements (not shown in figs 4d-e) may be flat mirrors placed in the image plane(s) of the lenses 104 and 108. It is noted, however, that the intensity of the laser beam may become very high in the focal point, especially if the M^2 is close to one. This involves the risk that the mirror coating on the mirror may be burned off or the mirror substrate may be damaged. In another embodiment, where this problem is avoided, the partially transparent reflective elements are spherical feedback mirrors placed in the distance of its radius of curvature from the image plane.

The embodiment of figs. 4d-e produces a focussed beam and still allows axis-independent magnification, removal of astigmatism and non-coinciding Fourier-planes of the FA- and the SA-axis. A common lens can afterwards be used to e.g. collimate the beam, focus it through a modulator, etc.

It is understood, that the two principles described above may be combined, e.g. by providing an axis-independent Fourier-transformation by two aspherical cylinder lenses that produce a focused beam in the FA and a collimated beam in the SA.

For example, in one embodiment, the beam may be focused onto the feedback mirror in the fast-axis direction. This corresponds to the setup illustrated in fig. 4d. The mirror may be flat in this direction because its surface is placed in the focal point. A spatial filter may be placed in the

Fourier-plane to remove noise as illustrated by filter 105 in fig. 1b. Behind the feedback mirror a third lens can be used to collimate the output and to act as a beam expander together with the FA Fourier-lens. This gives the benefit that ellipticity of the output beams can be removed by the beam expander that works on the fast-axis, only. Secondly the astigmatism can be removed through the collimation.

Along the slow-axis, a collimated beam may be used to produce the Fourier-plane as illustrated in fig. 4c. This gives the benefits that the magnification is large, which lowers the tolerance requirements to the mechanics of the mode-filter.

In general it is preferred, in order to obtain a good mode selection, that the lenses used in the laser system are (as much as possible) diffraction free. Thus, lenses such as achromats or aspheric lenses are preferred and, due to the high astigmatism, one-axis optics is preferred. High quality lenses improve the beam quality and facilitate the establishment of useful feedback in the laser system, since e.g. aberrations from lenses are avoided which would cause the individual modes to be mixed in the diffraction plane.

Hence, in the above different optical systems for providing a Fourier-transformation in a laser system according to the present invention have been disclosed.

Figs. 5a-c show schematic views of examples of a laser system without Fourier lenses.

The system of fig. 5a comprises a laser diode 101 as described above and a spherical mirror 501. The spherical mirror 501 is placed in the distance of its radius of curvature from the diode 101. Hence, the optical path length from the diode to the mirror for each angle of radiation θ is the same.

The mirror 501 comprises sections 502 of the sphere which are made partially reflecting and partially transparent, while the remaining surface 504 is made absorbing. Hence, a mode selective feedback in the far-field is achieved and two output beams 503 are provided.

It is noted that, alternatively or additionally to the mirror with different sections, spatial-filters between the diode and the mirror may be used. It is further noted that, if lenses etc. do not remove the astigmatism of the diode, it may be advantageous that the radius of the sphere is different in the FA- and the SA-direction.

It is an advantage of this system, where the far-field is used directly without Fourier transforming optics, that the external cavity is simple and short. It is understood, however, that the length of the cavity is limited by the rules of Fraunhofer-diffraction.
Figs. 5b-c illustrate another laser system without Fourier lenses where the mode selective feedback is achieved by means of plane feedback mirrors. Fig. 5b illustrates for a system with a single feedback mirror 510 providing feedback of a single lobe of a mode that closed loop feedback is only obtained for modes with normal incidence to the feedback mirror, as illustrated by arrows 512. Modes that are not incident normal onto the mirror are not reflected back into the diode 101 or are at least only partially reflected back into the diode, as illustrated by arrows 513. Furthermore, modes that are not incident normal onto the feedback mirror will not establish a closed loop path and, therefore, such modes are suppressed in comparison with the mode incident normal to the mirror. Fig. 5b shows a corresponding laser system with plane, partially reflecting feedback mirrors 510 and 511 for obtaining feedback of both lobes of a mode.

Figs. 6a-c illustrate examples of spatial filters for selecting spatial modes according to an embodiment of the invention.

As described above, when a far-field pattern or a pattern sufficiently close to a far-field pattern is present in e.g. a Fourier-plane produced by e.g. one of the optical Fourier-transforming systems described in connection with figs 4a-e, the mode selection may be carried out in such a plane. The mode selection is done by a spatial filter in the far-field or a Fourier-plane.

Fig. 6a illustrates an embodiment of a spatial filter. The spatial filter comprises two filter blades 601 and 602 defining an aperture in the form of a slit 603. Preferably, the front surfaces 604, 605, 606, and 607, i.e. the surfaces facing the laser diode, as well as the back surfaces 608 and 609 of the filter blades should have a low reflectivity, in order to avoid reflection and scattering of the non-selected modes. The edges 610 of the slit 603 should be sufficiently sharp to limit the diffraction of the beam. The areas 606 and 607 of the front surface are angled so reflections from non-selected modes are directed in a direction away from the diode. The edges 610 of the slit have a low roughness and define a straight line (orthogonal to the plane of the drawing) in order to obtain a well-defined mode selection. For example, the filter blades may be realized by razor blades or air slits. Preferably, the width and position of the slit 603 should be adjustable with micrometer resolution.

It is understood that the filter shown in fig. 6 may be used as a mode filter for one of the half planes of the Fourier-plane 103 in fig. 1a, i.e. the aperture 603 corresponds to one of the apertures 110 and 111 in fig. 1a. Furthermore, the filter shown in fig. 6 may be used as a filter in the high coherence axis, i.e. as filter 105 in fig. 1b. Hence, in one embodiment, the laser system of figs. 1a-b comprises three spatial filters of the type shown in fig. 6a: One for the FA-direction and one for each of the half planes of the Fourier-plane in the SA-direction. In one embodiment, the filters in the fast and slow axis may be combined to a single filter arrangement having 2d apertures.

Fig. 6b shows an embodiment of a spatial filter seen from the laser diode. Reference numerals 601 refer to the filter blades defining a slit 603, as

described above. Reference numerals 611 and 612 indicate schematic illustrations of the mode lines of the spatial modes. Hence, each of the lines 611 and 612 schematically represents a lobe of a spatial mode, where the mode corresponding to line 612 is selected by the spatial filter, while the modes 611 are prevented from passing through the filter. Reference numeral 613 refers to the z-axis which points into the plane of the drawing. As illustrated by fig. 6b, the filter blades should preferably be parallel to the mode lines 611 and 612.

Since the mode lines may not be perfect straight lines but rather bended due to e.g. imperfections in the optics etc, the rotation of the filter-blades 601 and 602 around the z-axis 613 is an optimisation parameter in the alignment of the laser system

Hence, the optimisation parameters for the alignment of each of the spatial filters include:

- The filter position: In the SA, this influences the selection of the mode; in the FA, this influences the edge cutting of the beam.
- The width of the filter aperture.
- The rotation of the filter around the z-axis.

Preferably, an alignment procedure of the filters is performed as an iterative adjustment of the above parameters while monitoring the resulting output.
Hence, preferably, the filters allow an independent control of the above parameters. The adjustments may be performed by μm-screws or similar devices. In more demanding cases e.g. piezoelectric technologies may be used. For automated optimisation pico-motors, dc-motors or the like can be used.

Fig. 6c illustrates a spatial filter integrated with a partially transparent reflective element. The filter comprises a filter blade or mirror substrate 621 having an edge 622. A partially reflecting/partially transmitting mirror stripe 623 having a width corresponding to the width of a single mode is placed at

the edge 622 of the filter blade. Hence, in this embodiment, the mirror surface is placed in the Fourier-plane. In this embodiment, no filter blade is provided in the centre of the beam profile, whereas the feedback mirror substrate 621 works as a filter in the outer part of the beam.

Fig. 7 illustrates the generation of dynamic gratings in the amplifying medium in a laser system according to an embodiment of the invention. As described above, the external cavity of a laser system according to the invention comprises at least one reflecting element, e.g. a mirror, a phase-conjugating mirror, a prism, or the like, to provide the optical feedback into the laser diode. Fig. 7 illustrates the optical feedback from a dual cavity generated by a laser diode 101 and two partially transparent reflecting elements 106 and 112.

It should further be noted that the leaser system of fig. 7 does not comprise separate mode-filters or optics. The mode selection in such a system relies on the fact that each mode propagates at a corresponding angle with respect to the surface normal 107 of the diodes front facet. Hence, the tilt angle of a flat mirror can therefore be adjusted to substantially only reflect one mode back into the laser diode. The other modes will not hit the diode. Hence, the mirrors function as mode filters.

The external mirrors 106 and 112 are partially reflecting mirrors where respective parts of the incident beams B1´ and B2´ are reflected as beams B3´and B4´, respectively. Corresponding other parts of the incident beams are transmitted as output beams 113 and 114, respectively. The laser diode may be regarded as a more advanced mirror which provides reflections at the AR-coating 703 of the front facet, the dynamical gratings 701 in the active region, and the HR-coating 702 on the back facet. The diode mirror does not return the beam back to the same cavity where the incident beam came from but redirects the incident beam to the other cavity. Thus, a dual optical cavity is obtained, where the beam of one cavity is dependent on the beam in the

other cavity. Inside the laser diode, the beams corresponding to beams B1', B2', B3', and B4' are denoted B1, B2, B3, and B4, respectively.

The output from the laser diode has an M-shaped profile in the far-field as was described above. For the purpose of the current description, it is assumed that such a far-field is present in the region of the mirrors 106 and 112. Therefore the mirror-region can be divided into two half-planes, the upper (corresponding to mirror 106) and the lower (corresponding to mirror 112) plane with respect to fig. 7. Hence, one peak of the M-profile is located in one of the half-planes and the other peak in the other half-plane. As described above, a mode in one half-plane corresponds to a mirrored mode in the other half-plane and vice versa. In principle these two mirrored modes are independent of each other, but they have mirrored properties.

However, the optical feedback by the mirrors 106 and 112 results in a coupling of the modes in one half-plane to the modes in the other half-plane. The ratio of coupling between the two modes can be controlled via the reflection coefficients of the reflecting elements 106 and 112. Large reflectivity results in a strong coupling through a strong feedback. However, this results in a low ratio of output power because most of the beam is used for feedback. On the other hand, a low reflectivity results in a weak coupling due to a weak feedback. Here the output power will be much higher than in the first situation. Preferably, in a completely symmetric feedback system, the reflectivity of each of the mirrors is between 10% and 50%. In situations where asymmetric feedback is desired, it is preferred that one of the mirrors has a reflectivity close to 100%, while the other mirror has a reflectivity between 5% and 50%.

If the reflection coefficients of the mirrors 106 and 112 are equal, a mode coupling with a symmetric strength is provided in both half planes. If the reflection coefficient of one mirror is larger than the reflection coefficient of the other, the intensity of the output beam in the corresponding half-plane will be less than the intensity of the output beam in the other half-plane. Hence,

an asymmetry is introduced in both the feedback and to the coupling of the modes. The difference in the intensity of the two output beams 113 and 114 is thus determined by the ratio of the reflection coefficients of the two reflective elements 106 and 112.

Hence, the feedback system not only provides optical feedback into the diode but also controls the level of symmetry/asymmetry in the intensities of both the output beams and the feedback beams. The feedback system further couples mirrored mode pairs to each other, and it controls the strength of the coupling vs. the ratio of output power.

In the following, the mechanisms inside the laser diode with mode-selective feedback are described.

The active region of the diode 101 acts as multi-layer structure, where multiple beam interference can exist due to multiple beam reflections at the coated facets 702 and 703 and transmissions at the interfaces of the layers. A beam that hits the surface of the medium in an angle of incidence θ is reflected multiple times and transmitted through the structure. The classical situation of multiple beam interference as such is described in e.g. Pedrotti, FL & Pedrotti, LS: "Introduction to Optics", Prentice-Hall international edition. In addition to the classical situation, in the present case of a laser diode, the layered structure provides gain in some of the layers. Thus, the multiple beams are amplified for each internal reflection in the diode medium instead of having the classical loss. If the amplification exceeds the losses in the amplifying medium, the intensity grows, and at a certain level the intensity may become so high that the material of the amplifying medium is damaged. The level at which this happens is determined by the number of reflection vs. the gain and the intensity of the incidence beam. The optical path length through the amplifying medium determines the amplification.

The back facet 702 of this layered structure is HR-coated. Therefore, most of the multiple beams are reflected back into the diode. The AR-coated front

facet 703 provides most of the output. This output can produce an interference pattern due to the normal properties of multiple beam interference.

Fig. 8 illustrates a calculated far-field interference pattern of a laser diode. Such a calculation includes a calculation of the multiple beam interference pattern as a function of the angle of incidence for a system with the properties of a laser diode. A subsequent calculation of the sum of all the interference patterns for each angle of incidence results in a curve as shown in fig. 8. The curve 801 represents the interference pattern seen in the far-field of a multimode laser diode. The calculation is here fitted to correspond to a measured far-field profile of the laser diode as shown in fig. 3a.

Curve 801 actually corresponds to a wrap-around curve for the real far-field without mode information etc. The calculated curve 801 suggests that modes located in the angle-intervals of constructive interference (indicated by reference numeral 802) should be used for the feedback. Modes located in angle-intervals of destructive interference (indicated by reference numeral 803) have low intensities and, therefore, they will provide a weak feedback.

The characteristic M-shape of the far-field profile is seen to have strong similarities with the calculated multiple beam interference patterns.

Hence, the far-field profile of the diode is strongly dependent on the properties of multiple beam interference inside the multi layered structure of the internal cavity of the diode. It is here important to notice that a lot of other effects are present as well, but multiple beam interference is an important effect.

The calculated curve 801 assumes that no gained spontaneous emission contributes to the curve. However, the part of the beam that contributes due to spontaneous emission would behave in the same way as a higher intensity of the input beam. Therefore this model is valid for free running diodes as

well as diodes that get an injection beam from either feedback or an external laser.

The up- and down turns inside the M-shape profile are caused by constructive- and destructive interference, respectively. Close to an angle of incidence of zero degrees the interference fringes are weak and they wash out each other. At larger angles of incidence the distance between the fringes become larger and strong interference exists. Hence, curve 801 provides an indication of the angular intervals 802 at which an additional gain is achieved due to the properties of constructive- and destructive interference compared with the normal level at the centre.

The edge of the M-shaped far-field is not defined by the multiple beam interference calculation but roughly by the width of the diode's emitter stripe vs. the length of the cavity of the diode. This information can be used to chop off the far-field profile above e.g. ±4 deg, which is the angle where destructive interference starts as illustrated by fig. 3a. For diodes with other geometries, other shapes of the M-profile may appear, e.g. with the edges of the profile being chopped off slowly. However, diodes with a sharp M-profile are preferred, because the modes at higher angles than the one with highest intensity are naturally removed by the diode. It is noted that other effects, such as scattering in the facet coating, divergence because of phonon pressure, higher order effects etc., also contribute to the resulting interference pattern. However, the above simplified linear model is useful to understand the laser system according to the invention.

In conclusion, the angle selected by the selection means and, thus, used for feedback and mode-selection, should preferably correspond to the angles that are "gain rewarded" by the diode, i.e. angles in regions 802 in fig. 8, as these modes are the best suitable modes for doing feedback in view of multiple beam interference. In the example of fig. 8, this corresponds to an angle of approx 4 deg. However, this value depends on the diode used.

The mode-selective feedback causes the feedback beams to be substantially single-mode beams. These beams are, due to the gain properties of the diode, amplified by stimulated emission in the active region of the laser diode.

Again referring to fig. 7, inside the diode 101, the beams B1, B2, B3, and B4 generate an interference pattern 701 with fringes having a fringe spacing of

$$d = \lambda/(2\sin\theta)$$

where λ is the wavelength of the beams and θ is the angle of propagation inside the medium.

For example, for an 830nm beam at an incidence of 4°, the fringe spacing is approx. 6μm. For example, in a 200μm wide emitter, 33 fringes may be present inside the diode at this angle.

The contrast in this interference pattern does not have to be the same in all areas of the active region of the diode, because the intensity of the beams can be different over the region due to asymmetric feedback and the properties of gain. The fringe contrast caused by two beams with beam irradiances I_1 and I_2, respectively, may be determined as

$$\text{Fringe contrast} = (I_{\max} - I_{\min})/(I_{\max} + I_{\min})$$

where

$$I_{\max} = I_1 + I_2 + 2\sqrt{I_1 I_2}$$

and

$$I_{\min} = I_1 + I_2 - 2\sqrt{I_1 I_2}$$

Hence, two beams with the same intensity give rise to the maximal fringe contrast of $4I_0$, where $I_1=I_2=I_0$. Hence, the visibility of the interference pattern depends on the size of the irradiance.

The differences in the contrast in an interference pattern is known to cause diffusion of free electrons, causing changes in the index of refraction that follow the pattern of the interference inside the diode. Consequently, a grating 701 is introduced in the diode. This grating is selective to wavelengths and propagation directions. The grating allows the beam of the mode that created it to exist, whereas it suppresses other modes, thereby providing an efficient mode selection inside the laser diode.

The created grating 701 is dynamical, i.e. it changes if the feedback beams B3' and B4' are changed. This grating can therefore be controlled by the external feedback system. The irradiance of the feedback beams controls the strength of the grating and the asymmetry, the ratio between the intensity of the feedback beams, controls the contrast in the grating.

The strength of the above grating decreases as the angle of incidence increases and the grating ceases to exist if the angle of incidence becomes too large, e.g. tens of degrees. This is due to the recombination of the free electrons, where the recombination time is directly proportional to the third order susceptibility that determines the strength of the grating. Consequently, small angles of incidence should be used, preferably smaller than $< 7°$. The efficiency of the grating depends on the depth of the dynamic grating lines. Hence, low angles of incidence give rise to a high efficiency and high angles low efficiency.

On the other hand, the selectivity of the grating is strongest for high angles and weak for small angles. Angles larger than approx. 3° are preferred.

Hence, at a preferred angle the overall most efficient grating exist as a compromise between the above effects of grating efficiency, grating

selectivity and zones of constructive interference. As an example, the region of 3.5 to 4.0° is preferred for the diode of the example of figs 3a-b. This has been verified by experimental results.

It is further noted that, due to the occurrence of four-wave mixing inside the laser diode, the output beam B1' is coupled to the output beam B2' and vice versa. Furthermore, the feedback beams B3' and B4' are coupled to each other as well. The four-wave mixing contributes to the creation of a grating with the same properties as the one created by the linear effects described above. Hence, the effect of four-wave mixing works as a stabilizing non-linear effect, thereby providing an even stronger mode-selective grating.

Hence, the conditions for the creation of an effective mode-selective grating inside the laser diode are:

- The angle for feedback should be selected so the angle is located within an interval of constructive interference as described in connection with fig. 8.
- The angle should be selected sufficiently small, preferably smaller than 7°, to ensure a large strength of gratings, which is related the recombination time of charges.
- The angle should be selected sufficiently large, preferably larger than 3°, in order to ensure an optimal diffraction efficiency.

Hence, the above conditions provide guidelines for finding a preferred interval for the angle of incidence. It is noted that the grating efficiency, strength and interference are dependent on the properties of the material and the geometry for the laser diode. Consequently, the linear- and the third-order effect contributing to the creation of dynamical mode-selective grating are controlled by the properties of the dual feedback system.

Fig. 9 shows a block diagram of a closed loop control system corresponding to an embodiment of the invention. The properties of the optical feedback system described above may be compared to a control system, resulting in a

description of the dual optical feedback system as an optical control system. Boxes 901a and 901b correspond to the spontaneous emission in the laser diode contributing to beams B1, B2, B3, and B4. Boxes 902a and 902b corresponding to the gain provided by the amplifying medium resulting in the output beams B1' and B2'. The reflectors 106 and 112 provide the feedback signals B4' and B3', respectively, and the output signals 113 and 114, respectively.

Hence, the control system of fig. 9 corresponds to a standard closed-loop system. The feedback signal is read optically by the reflective elements. All signals in this system are optically.

It is noted that the closed-loop system can be operated symmetrically, i.e. with feedback signals B3' and B4' of equal strength, as well as with different degrees of asymmetry in the feedback and, thus, in the output. The closed-loop system can even be used with properties close to those of an open-loop system, i.e. with one feedback beam much stronger than the other, but with the benefits of a closed-loop control system.

Figs. 10a-d show schematic views of examples of reflective members for use in an embodiment of the invention.

Fig. 10a shows a first embodiment of a reflective element. The reflective element 1001 comprises a single partly transparent mirror, where the two halves 106 and 112 of the mirror provide reflective elements for the two half-planes of the dual cavity. It is understood that the dashed line 1002 in fig. 10a is only added for illustration purposes. In this embodiment, the two halves of the mirror are not physically separated. A combination of the reflective elements 106 and 112 in a single mirror 1001 is possible, because in one embodiment the reflective elements are positioned parallel to each other in the same distance from the diode. Hence, in this embodiment, the reflective elements 106 and 112 have the same reflectivity, corresponding to symmetric feedback.

Alternatively, the reflecting areas 106 and 112 may be separated by a non-reflecting area, e.g. provided with an AR-coating or a none-reflecting element mounted onto the surface of the mirror.

Fig. 10b shows a second embodiment of a reflective element. The reflective element comprises a single, partly transparent mirror, where two sections 106 and 112 of the mirror are coated with reflective coatings providing different reflectivity.

By placing two mirror coatings with different reflectivity on the same substrate, two reflective elements 106 and 112 are provided which are aligned together, i.e. as a common unit, thereby ensuring an exactly symmetric alignment of both mirrors.

In the example of fig. 10b, the reflecting areas 106 and 112 are separated by a non-reflecting area 1004, e.g. provided with an AR-coating or a non-reflecting element mounted onto the surface of the mirror.

Fig. 10c shows a third embodiment of reflective elements. According to this embodiment, two separate mirrors 106 and 112 are provided having a gap 1006 between them. This embodiment provides additional degrees of freedom for the alignment, as both mirrors can be aligned independently, thereby reducing the requirements to the collimation of the beam emitted by the diode. If the beam emitted from the laser diode is divergent, each of the mirrors need to provide two degrees of freedom to be aligned:

1) Rotation around the FA-axis (Rot_{FA}) , and
2) rotation around the SA-axis (Rot_{SA}).

The aim of the alignment is to hit the diode straight back with as much of the feedback beam as possible and in the right angle.

Fig. 10d shows a fourth embodiment of reflective elements. According to this embodiment, two separate mirrors 106 and 112 are provided having a gap

between them. A spatial filter 1008 is placed in the gap. This filter can block out the centre modes of the diode which do not provide optimal feedback. It is noted that the alignment of a mirror having a centre filter may further require the alignment of a rotation around the z-axis in order to align the filter to the mode-lines.

It is noted that even though the filters shown in figs. 10a-d are rectangular, other shapes of mirrors may be chosen.

Note that a strong feedback does not depend on the reflectivity of the feedback elements only. The ratio of in-coupling into the diode also depends on the properties of Snell's law. This leads to the selections of optimal angles for feedback and the optimal reflectivity of the AR-coating on the front facet of the diode.

It is noted that the exit surface of the mirror, i.e. the surface pointing away from the diode, may be provided with an AR-coating, thereby reducing reflections from the second surface of the mirror.

In general, feedback mirrors are preferred with a high-quality surface-flatness, preferably of $\lambda/10$ or better, where λ is the wavelength of the laser beam, in order to ensure a high beam quality.

Fig. 11 shows a schematic view of a laser system producing four output beams according to an embodiment of the invention. The laser system comprises a laser diode 1101 with two output facets 1102 and 1103, each being coated with an AR-coating in order to generate output beams in both directions. The laser diode with two output facets has the same properties as the laser with a single output facet, i.e. the beams being emitted from output facet 1102 as well as the beams being emitted from output facet 1103 are effected by the dynamical grating in the active region of the diode, similarly to the laser system with a single output facet.

On both sides of the laser diode a dual cavity is provided, each comprising a Fourier lens 1108, a spatial filter 1109 and partially transparent reflective elements 1106 and 1112, similar to the system providing two output beams described above. Hence, the laser system of fig. 11 produces a total of four output beams 1113, 1114, 1115, 1116. It is understood that such a laser system does not produce more total power than a system with one output facet; the total power is merely distributed between the four beams.

Figs. 12a-b show schematic views of laser diodes with an integrated feedback system according to an embodiment of the invention.

Fig. 12a shows a laser system comprising a laser diode 1201 having angle-selective filters 1203 and 1204 integrated in the laser diode. The diode 1201 comprises an amplifying medium 1202, an HR-coated back facet 1226, angle-selective filters 1203 and 1204, an AR-coated front facet comprising two non-parallel sections 1207 and 1208 having an angle 2θ between their respective surface normals, where θ is the angle of emittance of the selected mode. The angle-selective filters 1203 and 1204 are arranged to selectively let beams 1215 and 1216 orthogonal to the surfaces of sections 1207 and 1208, respectively, pass while blocking beams propagating in substantially all other directions. The system further comprises external partially transparent reflective members 1211 and 1212 which provide feedback beams 1219 and 1220 and output beams 1223 and 1224 as described above. Hence, the laser system of fig. 12a provides a dual cavity laser system where the selection means are integrated into the laser diode.

A laser with integrated angle-dependent filter may be produced in several ways, for example:

- An angle dependent grating, hologram, or the like may be created in a suitable material (e.g. Si or InP). The gratings or holograms may be produced by electron-beam lithography, holographic lithography, nano-imprint lithography and other methods, thereby providing an optic filter. After the gratings or holograms have been produced, the optic filter is

attached onto the laser diode by means of integration of optical components known as hybrid integration.

- A monolithic technique for integration of the laser and filters into a single device may be used. The filter is produced by techniques similar to the procedure used above, i.e. gratings or holograms are produced by electron-beam lithography, holographic lithography, nano-imprint lithography or other methods. The gratings or holograms can be formed in the same material used for fabricating laser diodes, i.e. GaAlAs, InGaAs or the like.

In both cases, the external mirrors 1211 and 1212 provide the feedback so that coupling between the beams is achieved.

Fig. 12b shows an example of an integrated laser with two output directions. In this example, angle-selective filters 1203 and 1204 and external mirrors 1211 and 1212 are provided on both sides of the laser diode 1201 having output facets with non-parallel sections 1207 and 1208 on both sides, thereby providing four output beams 1223, 1224, 1233, and 1234.

The cross-section-shape of the integrated laser shown in figs. 12a-b may be shaped as indicated, it may be quadratic or it may have other shapes.

Figs. 13a-b show schematic views of laser diodes with an integrated feedback system according to another embodiment of the invention.

Fig. 13a shows a laser diode 1301 that comprises an amplifying medium 1302, a HR-coated back facet 1315, angle-selective filters 1303 and 1304, and a front facet with two non-parallel sections 1307 and 1308, as described in connection with fig. 12a. The integration of angle dependent filters can be produced by methods similar to those described above. According to this embodiment, the feedback mirrors 1311 and 1312 are integrated with the laser diode as well, thereby providing a single unit producing two output beams. The feedback mirrors 1311 and 1312 may be integrated with the

laser diode by the use of gratings, holograms or by a coating of the output facets. The filters 1303 and 1304 may further be combined with the feedback mirrors 1311 and 1312 in the same grating or hologram, so that the grating or hologram has a reflectivity of e.g. 0.5 at a certain angle (e.g. 6 degrees), whereas the reflectivity is close to 0 at angles different from 6 degrees (e.g. the reflectivity may be 0.05 at 6.5 degrees). The integrated mirrors provide the feedback so that coupling between all beams is achieved. The integrated laser produces two output beams 1323 and 1324.

Fig. 13b shows an example of an integrated laser having two output directions. In this example, angle-selective filters 1303 and 1304 and feedback mirrors 1311 and 1312 are integrated on both sides of the laser diode 1301 having output facets with non-parallel sections 1307 and 1308 on both sides, thereby providing four output beams 1323, 1324, 1333, and 1334.

Fig. 14 shows a schematic view of a laser system including a stack of single-emitter diodes according to an embodiment of the invention. As described above, inside the laser diode all the existing modes are mixed up in space, and mode-selection by spatial-filtering is not possible. In the Fourier-plane, e.g. created by a Fourier-lens, all the modes are separated into space. An angle inside the diode corresponds to a certain position in the Fourier plane or far-field outside the diode. Light propagating with a certain angle exists everywhere inside the diode. However, independently on its position inside the diode it will end up in a fixed position in the Fourier-plane or the far-field. Therefore, in the Fourier-plane it does not matter whether the beams originate from a single-emitter diode or from e.g. a diode bar.

Accordingly, the laser system according to this embodiment comprises a stack 1400 comprising a number of single diodes 1401, 1402, and 1403 that are stacked on top of each other, i.e. stacked in the direction of the high coherence axis (FA). Hence, the fast-axes of the single emitters 1401, 1402, and 1403 coincide.

This situation is similar to simply stacking a number of lasers systems as in figs. 1a-b with single emitter diodes on top of each other. The same lenses and the same filters etc. may be used to provide feedback to all the diodes.

In the example of fig. 14, the system comprises an optical component 1404, e.g. a Fourier lens, array cylinder optics, or the like, providing a common Fourier plane for all emitters. The system further comprises a spatial filter 1405 with two apertures 1413 and 1414 placed substantially in the Fourier plane of the optical component 1404. The system further comprises a partially transparent mirror 1406. The system provides output beams 1407, 1408, 1409, 1410, 1411, and 1412, i.e. the number of output beams is twice the number of diodes. The output beams from different emitters are not coupled to each other.

Fig. 15 shows a schematic view of a laser system including a bar of single-emitter diodes according to an embodiment of the invention. The laser system according to this embodiment comprises a bar 1501 comprising a number of single diodes 1502, 1503, and 1504 that are placed side by side, i.e. placed next to each other in the direction of their slow axes (SA). Hence, their slow-axes coincide.

Each of the emitters in a bar has the same properties as the emitter in a single emitter diode, and the properties of the Fourier-transform are still the same, too. Hence, the position where a mode ends up in the Fourier-plane is still dependent on its angle of propagation and not its position in the bar. Therefore it does not matter from which diode in the bar a mode has its origins. Consequently, the same configuration described in connection with figs. 1a-b a single diode may be used in the case of a diode bar as well. In fig. 15, this is illustrated by a Fourier lens 108, a spatial filter 109 providing apertures 110 and 111 and mirrors 106 and 112. The system of fig. 15 produces two output beams 113 and 114.

It is noted that in the examples of figs. 14 and 15, stacks and bars with three single emitters are shown. However, it is understood that bars and stacks with a different number of diodes may be used as well. It is further understood that a filtering in the fast axis as described in connection with fig. 1b may also be applied here.

Furthermore, an array may be regarded as a stack of bars. The setup for using an array may be regarded as a stack of bar systems, thereby providing the same number of beams as seen for the stack. The lenses and the filters can be common for all the diodes; alternatively, array optics may be used.

One should notice that the errors and, thus, the beam quality factor will be increased when more than one diode is used. However, the brightness and the beam quality factor of e.g. an array laser with dual feedback according to the invention will be significantly improved compared to a corresponding free running array.

Today, the standard available laser diodes have 1xN modes. Future diodes may have MxN modes and two low coherence axes. It will be appreciated that the invention may be applied in connection with such diode types as well, both as single units or arranged in bars, stacks or arrays.

Hence, in the above the use of bars, arrays, stacks, etc., in connection with a dual feedback laser system according to the invention is disclosed. It is an advantage of these kinds of diodes compared to a single emitter that a higher output power is achieved from the laser system.

Fig. 16 shows a flow diagram of a method of aligning a laser system according to an embodiment of the invention. In order to realize the optical feedback and obtain high beam quality, all the components in the laser system should be aligned with respect to those degrees of freedom that affect the beam quality, i.e. with respect to the rectilinear axes and rotation

axes. Preferably, the accuracy of the positioning stages should be in the micrometer range or below.

It should be noticed that the alignment of the laser diode(s) itself is important as well. The centre mode should follow the z-axis and the tilts of the diode should be removed. A badly aligned diode can make the rest of the alignment very difficult.

In the following reference will also be made to the system of fig. 17 which shows a schematic view of a configuration of a laser system during alignment according to an embodiment of the invention.

The laser system of fig. 17 corresponds to the system described in connection with figs. 1a-b. The system comprises a laser diode, one or more Fourier lenses 108, a spatial filter 109 with two apertures 110 and 111, and two mirrors 106 and 112, as described in greater detail above. It is noted that the system may comprise further components not shown in fig. 17 that work in the high coherence axis, e.g. as shown in fig. 1b.

For the purpose of the alignment of the above components, the system further comprises a beam scanner 1704 or other device for viewing the far-field profile of the beam. A beam-splitter 1701, e.g. a wedge, a plane-plate or the like, is placed between the lens 108 and the spatial filter 109, so a part 1702 of the beam is reflected into the beam scanner 1704 which is placed in the Fourier-plane 1703. For example, the beam splitter may extract a small fraction, e.g. 1% of the beam, while letting the major fraction, e.g. 99%, pass towards the filter 109.

Furthermore, two power meters 1705 and 1706 are placed in the paths of the two output beams 113 and 114, respectively, to measure the individual power or the total power of the two outputs. The power meters are used to determine the degree of symmetry in the output power of the two beams.

It is noted that additional lenses may be added to match the apertures of the instruments 1704, 1705, and 1706.

Now referring to figs. 16 and 17, a method of aligning a laser system according to an embodiment of the invention is described.

In an initial step 1601, the characteristics of the laser diode are determined. This may include a determination of the far-field profile, the threshold current, the slope efficiency, the alignment on the mount, microscope investigations of the emitter(s), etc. The investigation has the purpose of identifying possible unsuitable diodes and to establish knowledge of the far-field profile etc. which is important for the establishment of efficient mode-selective feedback.

Subsequently, in step 1602, the components, i.e. lenses etc., of the laser system are pre-aligned and it is verified that the spectrum in the diffraction plane matches the view of the known far-field e.g. by means of beam scanner 1704. This ensures that the right position of the diffraction plane is found. Thereby the mode-filters can be placed in the right position and that mode-selection can be done.

In step 1603, a first attempt to establish feedback is carried out, initially without necessarily attempting to achieve mode-selective feedback. During this step a diode current just above the threshold current of the diode is used, in order to avoid diode hazards. In this step, a scanning over the rotation angles of the feedback mirrors 106 and 112 may be performed while observing the pattern in the diffraction plane 1703 as measured by the beam scanner 1704. When a change in the diffraction plane pattern is observed, the mirror is aligned to provide feedback into the diode 101. Next the interval of rotation angles is determined in which feedback is detected. The mirror is aligned to the centre of this interval.

In particular, according to one embodiment, each of the mirrors 106 and 112 may be aligned according to the following procedure:

- The diode current is set just above threshold.
- A 2D-scan of the mirrors is performed by varying the rotation angles with respect to rotations in around the high and low coherence axes Rot_{FA} and Rot_{SA}, respectively.
- When the feedback beam hits the diode, the far-field profile will change.
- A scan is performed to determine the Rot_{FA} and Rot_{SA} limits within which feedback is present. The corresponding centre position of the two angular directions are selected as the position of the corresponding mirror.

When the feedback has been established, the mode-selection filters 109 are adjusted to select a mode for the feedback. The first step in the process of getting dual feedback is actually to generate completely asymmetric feedback, thereby increasing the power in the mirrored mode to be used for the second feedback. Hence, the subsequent selection of the mirrored mode is facilitated.

Accordingly, in step 1604, filter aperture 110 is fully opened or, in case of separate spatial filters, one of the filters may be removed. Furthermore, the corresponding mirror 106 is blinded off. Hence, the feedback from mirror 106 is disabled.

In step 1605, the feedback from mirror 112 is optimised: The width of the aperture 111 is set to match the width of a mode, e.g. as estimated from the far-field profile or as calculated. Initially, the mode-filter aperture 111 is placed outside the beam. The laser diode 101 is turned on just above threshold. The aperture 111 is moved into the beam and its position is optimised according to the description of the mode selection in connection with fig. 7. During this step, the feedback mirror 112 and the filter aperture 111 may be adjusted iteratively while observing the far-field pattern measured by the beam scanner 1704. Fig. 18 shows an example of a desired

far-field profile compared to a far-field profile without feedback. It is noted that possible filters (not shown in fig. 17) in the high coherence axis may also be adjusted during this step in order to optimize the feedback.

Fig. 18 shows a far-field profile obtained during alignment of a laser system according to an embodiment of the invention. The solid line 1801 corresponds to the diode far-field profile with total asymmetric feedback measured by a beam scanner, while the dotted line 1802 corresponds to the diode far-field profile without feedback. This diode was a 3W diode by Coherent Inc. with an emitter size of 200µm x 1µm x 1mm. The free running output power was 3W. After the feedback was applied a power of 0.8W be found in the right peek within an $M^2_{50\%} < 3$. According to the invention, providing dual feedback an the introduction of dynamical gratings inside the diode further improves the result.

Hence, mirror 112 and filter aperture 111 are aligned to obtain a narrow and strong peak in the far-field profile.

Again referring to figs. 16 and 17, once the filter aperture 111 is aligned, the alignment process continues at step 1606. In step 1606, the filter aperture 110 is adjusted (still without feedback from mirror 106) to only let the high peek that was obtained in the previous step pass, thereby selecting the mirrored mode of the mode selected in the previous step.

In subsequent step 1607, the dual feedback is iteratively optimised. First, the laser diode is turned off, the access to feedback mirror 106 is re-established, and the laser diode is turned back on, thereby reactivating the feedback from mirror 106. Now the positions of the filter aperture 110 and the orientation of the mirror 106 may be fine tuned, in order to achieve two output peeks that are as narrow as possible, and to optimise the system so instabilities due to mode-competition are avoided.

Finally, in step 1608, the diode power is scaled up by increasing the drive current. However, this has the effect that the distance between the two mode-filter apertures 110 and 111 should be increased symmetrically around the center 107, in order to select the best mode as discussed in connection with fig. 7. Again, this may be achieved by an iterative adjustment. It should be noted that each type of diode corresponds to a maximum current. If this current is exceeded the diode will be damaged. The maximum current is dependent on the feedback properties and the properties of the diode. This limit should be found for each diode/feedback combination in order ensure a long lifetime of the laser diode system.

After alignment, the beam-splitter 1701, the beam scanner 1704 and the power meters 1705 and 1706 may be removed. Alternatively, the beam-splitter 1701 may be left in the system, and the beam scanner may be replaced by a power measuring device. During operation of the laser, such a power measurement may be used as a feedback signal for a control system controlling the drive current of the diode, thereby obtaining a power stabilization of the laser.

It is understood that the above alignment may be automated if the adjustment devices used to adjust the mode filters and the feedback mirrors are motorised or can otherwise be operated automatically. In this case, an automatic alignment routine may be executed, e.g. controlled by a suitable programmed microprocessor, computer, or the like. For example, during such a routine, two parameters may be varied at a time, e.g. the rotations of a mirror around two axes, the width and position of a filter aperture, etc. The automated routine may then select the combination of the parameters corresponding to a predetermined criterion, e.g. the parameter values providing the highest output measured by the power meters 1705 and/or 1706, the values resulting in the highest peak detected by the beam scanner 1704, or the like.

It is further understood that the above alignment may be based on the output power measurements alone, i.e. in a setup without a beam scanner.

Fig. 19 shows examples of far-field profiles of a laser system according to an embodiment of the invention. After the feedback has been established and the output from the laser system has been obtained, the far-field profile of the laser diode measured by the beam scanner 1704 has a shape as illustrated in fig. 19. Reference numerals 1901, 1902, and 1903 refer to profiles corresponding to different levels of success regarding the output power vs. beam quality. All three curves show a twin lobe structure with two lobes corresponding to the two output beams. Curve 1901 shows the preferred result where the total amount of available power is substantially concentrated into small spatial angles around the peaks 1905 and 1906, and the beam quality factor M^2 has a low value, e.g. less than two. Note, that fig. 19 illustrates the far-field profile and not the output from the feedback mirrors. The output beams from the feedback mirrors are further restricted by the mode-filter. The curves 1902 and 1903 correspond to increasingly lower level of success, where less power is concentrated in the peaks. The area 1904 below curves 1902 and 1903 correspond to a power loss, because these parts of the beam are removed by the mode-filters. Possible reasons for this power loss in an aligned dual feedback system include aberrations in the system, bad alignment etc., causing a weak mode-suppression and, thus, a lower beam quality and less output power.

Fig. 20 shows a schematic view of a laser system according to an embodiment of the invention including a modulation prior to a polarization coupling. For many applications it is required to modulate the laser beam so that an alternating sequence of on and off periods is achieved. The following example shows how this may be achieved by means of using acousto-optic modulators, electro-optic or other modulator devices.

In the embodiment of fig. 20, a laser system according to the invention comprises a laser diode 101, a Fourier lens 108, a filter 109 with two

apertures 110 and 110 and two partially transparent mirrors 106 and 112. The above components were described in greater detail above. According to this embodiment, the two output beams 113 and 114 from the partially transparent mirrors 106 and 112, respectively, are fed into corresponding modulators 2001 and 2002, respectively. The modulators 2001 and 2002 receive a common excitation signal from an control unit 2000. The modulators used in this configuration may be acousto-optic modulators or other modulator types. The output beams 113 and 114 are continuous wave (CW) beams and can be turned on/off by an electrical or optical signal to the modulator driver. Hence, modulated beams 2003 and 2004 are generated.

In one embodiment, after the modulation, the modulated beams 2003 and 2004 are coupled by a polarization coupling into the same geometrical path and combined into one beam 2008. In the embodiment of fig. 20, the beams 2003 and 2004 are coupled by a polarization coupler 2007 in order to produce a single modulated beam 2008. The polarization coupling is achieved by rotating the polarization direction of one beam (beam 2004) by feeding the beam through a half-wave plate 2005. The resulting beam 2006 is combined with beam 2003 by the polarization coupler 2007.

In an alternative embodiment, each of the modulators may receive a different excitation signal. For example, a modulated beam with a DC-level may be generated by modulation of one of the two beams and subsequent coupling of the modulated beam and the continuous beam.

Fig. 21 shows a schematic view of a laser system according to an embodiment of the invention including a modulation after a polarization coupling. A laser system as described above provides two output beams 113 and 114. According to this embodiment, the output beams 113 and 114 are polarisation coupled directly by means of a half wave plate 2005 and the polarisation coupler 2007, as described above. A modulator 2102 is placed after the polarization coupler 2007, i.e. in the combined output beam path 2101 of the polarisation coupler 2007, thereby only requiring one modulator.

The modulator 2102 should be independent of the polarization direction of the beam 2101, because the beam 2101 is polarized in two orthogonal directions.

Hence, in the above examples, a modulation of the output of a laser system according to the invention is achieved which provides a high level of stability.

Fig. 22 shows a schematic view of a laser system according to an embodiment of the invention including a modulation. A laser system as described above provides two output beams 113 and 114. According to this embodiment, the output beams 113 and 114 are focussed by a lens 2201 into a modulator 2202 that is placed in the focus point of lens 2201. The modulated beams are focussed by a lens system 2203, e.g. two focus lenses, into a common focus point on a plate 2204. Hence, only a single modulator is required for modulating both beams.

For example, the plate 2004 may be a plate of a Computer to Plate (CtP) to be exposed. For example, the position of the focus point in the z-direction can be controlled by an auto focus system using a telescope.

Figs. 23a-b illustrate the use of a laser system according to an embodiment of the invention in an internal drum image setter. Figs. 23a-b show a side view and a view along a central axis of an internal drum of a computer-to-plate (CtP) image setting system, respectively.

The system comprises a cylindrical drum 2301 having an inner surface onto which a plate 2302 of a light sensitive material can be mounted. For example, some commercially available CtP plates are exposed at 830nm. In order to expose the plate 2302, a laser beam 2304 is directed along the longitudinal centre axis of the cylinder 2301. Inside the cylinder, a mirror 2303 is pivotally mounted, i.e. during operation it rotates around the direction of the incoming beam 2304. The mirror directs the laser beam 2304 onto the plate 2302. When the mirror rotates around the longitudinal axis, different points 2305 of

the plate are exposed. If the mirror is further moved along the longitudinal axis, the entire plate may be exposed. Hence, the mirror 2303 is mounted on a support 2306 which is movably mounted inside the drum.

The output from the CtP machine is normally four exposed plates; one for of each of the colors red, blue, yellow and black. In a printing machine, each of these plates is then used to print one color at a time.

The distance from the mirror to the inner surface of the drum is determined by the size of the plates to be exposed. Preferably, the laser beam should be focussed to a small spot size on the plate in order to ensure high-quality printing. Furthermore, the focussed beam should have a high intensity, in order to reduce the exposure time.

In order to expose such a plate in reasonable time (some minutes) in a resolution with a dot size at 10μm, a minimum of 8W optical power at 830nm is needed in the focal point 2304 on the plate. The rotation speed of the mirror is in tens of thousands rpm.

Fig. 24 shows a schematic view of an internal drum image setter including a laser system according to an embodiment of the invention. According to this embodiment a laser system as described in connection with fig. 20 produces an output beam 2008. The output beam is focussed by a lens system 2401, e.g. including auto-focussing systems, zoom optics, or the like, on the rotating mirror 2303 of the internal drum system. Hence, by combining a laser system according to the invention with an internal drum image setting system, an exposure of a dot with a size of 10μm is achieved by focusing the beam onto the drum.

It is an advantage of the laser system according to the invention that it provides a high-power beam in a suitable frequency range which can be focussed over a long distance.

It is a further advantage of the laser system according to the invention that it is compact. Consequently, a laser system according to the invention may be mounted on the same carriage 2306 as the mirror 2303 and, thus, moved along the longitudinal axis in the centre of the drum. Hence, the optical path length from the laser system to the focal point is constant. Since the laser system according to the invention is compact, the entire optical system may be placed inside the drum, thereby providing a particularly efficient and compact system with a short and constant optical path length. The path of the focus point on the plate is a helix in which the beam can be turned on and off.

Fig. 25 shows a schematic view of an internal drum image setter including a laser system according to another embodiment of the invention. According to this embodiment, a laser system similar to the system of fig. 24 is used. However, according to this embodiment, the polarisation coupler 2007 is replaced by a focussing optics 2501. Hence, the two modulated beams 2003 and 2006 are focussed onto the drum 2301 via the rotating mirror 2303, as described above.

Preferably, the focus point on the drum should be a circle or a square with a Gaussian intensity distribution. However, due to the coherence properties of the two beams, interference stripes will be formed across the focus spot, which will create a non-uniform intensity distribution. A solution to this problem is to insert a quarter wave plate 2505 in one of the beams. Thus, one beam (2003) is linearly polarized and the other (2006) is circularly polarized, thereby inhibiting interference stripes at the focus point. The same method may be extended to a larger number of beams than two beams.

Figs. 26a-b show a schematic view of a laser system according to an embodiment of the invention.

A laser system according to this embodiment of the invention generates mode-selective asymmetric optical feedback from an external cavity of one or

more multimode laser diode(s) 101. Spatial filters 109 placed in a diffraction-plane 115 of an optical component 108, e.g. a Fourier-lens, or in the far-field of the optical output of the laser diode 101, together with an external reflective component 2601, generate an asymmetric mode-selective optical feedback into the laser diode 101. This causes the output beam properties to change and output beam 113 with an M^2 value less that two and with an improved brightness is achieved.

The overall power of the multimode low coherence axis is concentrated into a single-mode with a good beam quality corresponding to the single-mode of the high coherence axis.

Fig. 26a shows a planar view of the laser system in a plane of low coherence including the low coherence axis (SA), while fig. 26b shows a planar view of the laser system in a plane of high coherence including the high coherence axis (FA).

Referring to fig. 26a, the laser system comprises a multimode diode laser 101 having a light-emitting active area on a front facet 116. In the direction of the low coherence axis (SA), the emitted light corresponds to a plurality of spatial modes, each corresponding to a twin-lobe profile around the optical axis 107 generally designated as z-axis. The laser system further comprises a Fourier lens 108 having a corresponding diffraction plane 103. A spatial filter 109 is placed in the diffraction plane 102. The spatial filter provides two apertures 110 and 111, each selecting a part of the emitted light beam corresponding to the lobes of a selected spatial mode. For examples, the spatial filters may provide two slits 110 and 111. The laser system further comprises a reflective component 2601 reflecting the mode selected by the aperture 111 back into the laser diode. According to this embodiment, the reflective component 2601 preferably reflects substantially all of the incident light back into the diode, thereby providing feedback for the selected mode.

Hence, the laser system of this embodiment provides a single output beam 113.

By placing a mode selective filter substantially in the Fourier plane 103 rather than performing simple beam cutting of the output beam in a distance from the Fourier plane the beam quality factor M^2 is improved.

According to the invention, the two filter apertures 110 and 111 in the SA Fourier-plane are adjusted to each select a mode that can be mirrored in the z-axis 107, i.e. at angles θ and -θ, respectively. That is, one filter selects the N-th peak in one half-plane and the other filter selects the N-th peak in the corresponding other half-plane with respect to the z-axis in fig. 1a.

Hence, according to this embodiment, the feedback mirror 2601 and the filter aperture 111 provide mode selective feedback. The corresponding mirrored mode is selected by the aperture 110 in the opposite half plane of the diffraction plane, thereby providing a substantially single mode output beam 113 with improved beam properties.

Now referring to fig. 26b, a frequency filtering is performed in the high coherence axis, thereby improving the beam quality along this axis, as well. The reason for this is that imperfections in e.g. the optical components lower the beam quality of this axis and reduce the beam quality of the feedback beams, thereby reducing the beam quality of the output, too. The frequency filtering is performed as a spatial filtering in the diffraction plane of a Fourier lens. Hence, the laser system comprises a Fourier lens 104 corresponding to a diffraction plane 102. A spatial filter 105 for selecting a part of the emitted beam in the direction of the high coherence axis (FA) is placed in the diffraction plane 102.

In the high coherence axis of multimode diodes usually only one mode is present. Hence, a mode selecting filter is not necessary in this direction. However, filtering of the beam in the FA-direction by the filter 105 increases

the beam quality, as it removes noise e.g. due to diffraction, aberrations etc., due to optical elements, or the like.

The individual components of the above laser system have been described in more detail above.

It should be noted that the above-mentioned embodiments illustrate rather than limit the invention, and that those skilled in the art will be able to design many alternative embodiments, including embodiments that combine features of the embodiments described above, without departing from the scope of the appended claims.

Furthermore, a laser system according to the invention may be used in a large number of fields, including the graphical industry, telecommunications, the medical industry, material science, etc.

In some applications the laser system may be combined with other optical techniques. For example, in the graphical industry UV-lasers with high power have been a long-felt need. Hence, by combining a laser system according to the invention, e.g. with a diode in the region of 780-940nm, with a frequency doubler, one or more UV laser beams may be achieved. For example, when a 780nm laser beam from a laser system according to the invention is frequency doubled, a 390nm beam is obtained.

In particular in connection with frequency doubling, it is an advantage of the invention that it provides an output beam with improved coherence properties and with a low M^2, thereby providing a high efficiency of the frequency doubling by Second Harmonic Generation (SHG) in a crystal like e.g. LBO, KTP etc. Frequency doubling as such is known in the art, see e.g. Robert W. Boyd, "Nonlinear Optics", Academic Press (1991). Efficiencies of tens of percent are possible.